

The Magnetic Fields of the Quiet Sun

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Abstract. This work reviews our understanding of the magnetic fields observed in the quiet Sun. The subject has undergone a major change during the last decade (*quiet revolution*), and it will remain changing since the techniques of diagnostic employed so far are known to be severely biased. Keeping these caveats in mind, our work covers the main observational properties of the quiet Sun magnetic fields: magnetic field strengths, unsigned magnetic flux densities, magnetic field inclinations, as well as the temporal evolution on short time-scales (loop emergence), and long time-scales (solar cycle). We also summarize the main theoretical ideas put forward to explain the origin of the quiet Sun magnetism. A final prospective section points out various areas of solar physics where the quiet Sun magnetism may have an important physical role to play (chromospheric and coronal structure, solar wind acceleration, and solar elemental abundances).

1. The Quiet Revolution

Our understanding of the quiet Sun magnetic fields has turned up-side-down during the last decade. The quiet Sun was thought to be basically non-magnetic, whereas according to the current views, it is fully magnetized. So magnetic as to dominate the magnetic flux and energy budget of the full Sun even during the maximum of the solar cycle (Sánchez Almeida 2003, 2004; Trujillo Bueno et al. 2004). Of course, quiet Sun magnetic fields are highly disorganized, so that their detection is far more complicated than that of active regions, which explains why they have been elusive for so long (see § 2). If one would have to identify a divide line for the transition, we would choose as landmark the numerical simulation by Cattaneo (1999a). It shows how the interplay between magnetic fields and surface convection produces an extraordinary complex magnetic field which, despite its vigor, remains almost invisible to observations due to cancellations (Emonet & Cattaneo 2001). The residuals left by such magnetic field, whose average field strength exceeded 100 G, were perfectly consistent with observations of the Zeeman polarization signals, the Hanle depolarization signals, and the Zeeman broadening (Sánchez Almeida et al. 2003a). The presence of such intense magnetic field is now clearly favored by observers (e.g., Domínguez Cerdeña et al. 2003a; Trujillo Bueno et al. 2004; Lites et al. 2008; Pietarila Graham et al. 2009; Jin et al. 2009) and theoreticians (e.g., Vögler & Schüssler 2007; Pietarila Graham et al. 2010), with some notable exceptions (e.g., Spruit 2010). This sudden drastic change in the way we perceive the quiet Sun can be appropriately called *revolution*, as we state in the title of the section. Most of the solar surface used to be non-magnetic whereas now it is

magnetic. A wealth of previously ignored magnetic structures have entered into being. They participate in the solar activity processes, and certainly determine some of the global magnetic properties of the Sun (see § 7). We dub the revolution *quiet* because it refers to the quiet Sun but, more importantly, because the profound change we are undergoing is seldom properly acknowledged. A proper acknowledging is basic for at least two reasons. (1) The study of the quiet Sun magnetic fields requires upgrading of the traditional magnetometry techniques, since all traditional approaches are prone to serious bias (§ 3). (2) We have not reached the end of the change yet. Our ideas are still in evolution, and we need to be prepared for the necessary update in a short time-scale.

This paper aims at summarizing the main observational properties of the quiet Sun magnetic fields. However, the paper begins with the theoretical ideas put forward to explain the origin of the quiet Sun magnetic fields (§ 2). The section comes first to set up the scene, i.e., to put forward the complicated magnetic field to be expected from theoretical grounds. It should be considered either as inspiration for a proper diagnosis, or as a caveat to avoid misinterpreting the observations. This admonitory section is followed by a description of the observational biases to be expected (§ 3). We then address specific properties of the quiet Sun magnetic fields: the distribution of magnetic field strengths and unsigned magnetic flux (§ 4), the distribution of magnetic field inclinations (§ 5), and the time evolution of the signals on short time-scales (§ 6.1) and during the cycle (§ 6.2). § 3 also addresses the line profile asymmetries, whereas § 6.1 describes the recent finding of loop emergence in the quiet Sun. The final § 7 is devoted to discuss various areas of solar physics where the quiet Sun magnetism, traditionally neglected, may have an important physical role to play.

2. The Origin of the Quiet Sun Magnetic Fields

To the best of our knowledge, three scenarios have been put forward to explain the origin of the quiet Sun magnetic fields. They may be debris from decaying active regions (e.g., Spruit et al. 1987). This possibility seems to be unlikely due to the large differences in the time-scale and magnetic flux of active regions and the quiet Sun (Sánchez Almeida et al. 2003b; Sánchez Almeida 2009). Active regions vary on time-scales of 12 years as compared to minutes, the time-scale characteristic of quiet Sun fields (e.g., Lin & Rimmele 1999; Zhang et al. 1998, and § 6). There is also an order of magnitude difference in unsigned magnetic flux in favor of the quiet Sun – the active regions present an unsigned flux density during solar maximum of some 15 G (e.g., Harvey-Angle 1993; Sánchez Almeida et al. 2003b) whereas we will be defending some 1 hG for the quiet Sun (see § 4). The second possibility is that quiet Sun fields result from the operation of a turbulent dynamo driven by the external convective layers (Petrovay & Szakaly 1993; Cattaneo 1999a; Vögler & Schüssler 2007; Pietarila Graham et al. 2010). Such dynamos seem to be unavoidable for a wide class of chaotic flow fields – see Childress & Gilbert (1995); Cattaneo (1999b). The topology of the resulting magnetic field is very complex, with mixed polarities coexisting up to the small resistive scales, which in the solar photosphere are smaller than 1 km (e.g., Schüssler 1986). Turbulent dynamos have a fast exponential growth rate, comparable to the turn-over time-scale of the motions, and the magnetic energy resides at the smallest (resistive) spatial scales. The magnetic energy $\langle B^2 \rangle / (8\pi)$ is a significant fraction χ of the kinetic energy that drives the dynamo $\langle \rho u^2 \rangle / 2$, so that

$$\langle B^2 \rangle^{1/2} \simeq 130 \text{ G}, \quad (1)$$

for an efficiency χ of 5%, assuming typical values for the granular motions at the base of the photosphere (density $\rho \simeq 3 \times 10^{-7} \text{ g cm}^{-3}$, velocity $u \simeq 3 \text{ km s}^{-1}$; e.g., Stein & Nordlund 1998, Fig. 5). Turbulent dynamo magnetic fields reproduce many observed properties of the quiet Sun magnetism, although this agreement is equally good if the complexity of the magnetic field is not due to the dynamo action but to the interaction of a preexisting magnetic field with the granular motions (e.g., Khomenko et al. 2005b; Stein & Nordlund 2006). Because of this reason, and to overcome difficulties of the first turbulent dynamo simulations, Stein & Nordlund (2002) proposed that the turbulent dynamo is not confined to the surface but it operates in the entire convection zone. Such conjecture represents the third possibility for the origin of the quiet Sun magnetic fields offered in the literature.

3. Tangling and Observational Bias

As we mention above, the numerical simulations predict a complex magnetic field, tangled to unresolved scales, having all magnetic field strengths (from 0 to 2 kG^1) and all inclinations (from 0 to 180°). The tangling occurs at such small-scale that most circular polarization signals disappear at the observed spatial resolution (e.g., Emonet & Cattaneo 2001). The most recent account of this effect predicts that at least 80% of the signals existing in the turbulent dynamo simulations of Vögler & Schüssler (2007) are not observable at $0''.3$ (Pietarila Graham et al. 2009), i.e., with the kind of best resolution achieved nowadays characteristic of the Hinode satellite (Kosugi et al. 2007; Tsuneta et al. 2008). In addition to this cancellation, many methods commonly used in Zeeman diagnostics have been claimed to bear their own specific biases. The measurements provide ill-defined averages of the mean properties in the resolution element, but the weighting depends on subtleties of the method, including the used spectral line. Among the claims in the literature, the polarization signals of the near IR line Fe I $\lambda 15648$ weaken in kG magnetic concentrations smeared by the vertical gradient of magnetic field (Sánchez Almeida & Lites 2000), the Mn I lines with hyperfine structure (HFS) are very sensitive to temperature and they tend to vanish in kG magnetic concentrations (Sánchez Almeida et al. 2008), and the pair Fe I $\lambda 6301, 6302$ cannot distinguish between kG-cold plasmas and hG-hot plasmas (Martínez González et al. 2006). The problem of spatial smearing is traditionally overcome using Hanle effect induced depolarization signals (e.g., Stenflo 1982; Faurobert-Scholl 1993; Landi Degl'Innocenti & Landolfi 2004). In this case a spatially unresolved randomly oriented magnetic field still leaves a residual, that can be measured and interpreted to infer magnetic properties. However, the Hanle effect signals are not sensitive above the so-called Hanle saturation field strength, which varies from spectral line to spectral line, but which seldom exceeds 1 hG. Hanle signals are therefore inadequate for diagnosing field strengths in the hG and kG regime. Table 1 lists these and other potential biases pointed out in the literature, with the original references included for the interested reader to consult.

Highly asymmetric Stokes profiles characterize the polarization signals of the quiet Sun. Their mere presence provide a direct model-independent indication of the

¹The upper limit is set by average gas pressure at the base of the photosphere, so that if this field strength is exceeded then the magnetized plasma cannot be in mechanical balance within the photosphere, and the imbalanced magnetic forces work to drop the field strength in a short (Alfvén) crossing-time scale; ~ 5 sec in a structure 50 km wide – see, e.g., Schüssler (1986).

Table 1. Biases when measuring quiet Sun fields as identified in the literature

Spectral Line	Type*	Potential Bias	Reference
All	Z	no polarization for $B \gtrsim 1.8$ kG	[1]
Temperature sensitive	Z	weaken with increasing field strength	[2]
HFS Mn I lines	Z	weaken to disappearance in kG	[3]
Fe I $\lambda 6301$ & 6302	Z	cannot distinguish kG-cold plasmas from hG-hot plasmas	[4]
Fe I $\lambda 6301$ & 6302	Z	produce false kG when noisy	[5]
Fe I $\lambda 15648$	Z	magnetic gradients make it weaken in kG	[6]
All	H	saturated for $B \gtrsim$ a few hG	[7]
Sr I $\lambda 4607$	H	the assumed distribution of B determines the mean field	[8]
C_2 & Sr I $\lambda 4607$	H	inconsistent results	[9]

* Physical mechanism responsible for the polarization: Z for Zeeman effect, and H for Hanle depolarization

[1] Sánchez Almeida (2000)

Harvey & Livingston (1969) [2]

[3] Sánchez Almeida et al. (2008)

Martínez González et al. (2006) [4]

[5] Bellot Rubio & Collados (2003)

[6] Sánchez Almeida & Lites (2000); Socas-Navarro & Sánchez Almeida (2003)

[7] Stenflo (1982); Landi Degl'Innocenti & Landolfi (2004)

Sánchez Almeida (2005) [8]

[9] Trujillo Bueno et al. (2004)

complexity of the magnetic fields. If our resolution elements were sufficient to resolve the magnetic structure, so that the plasma properties could be regarded as constant in the pixel, then Stokes V should be perfectly antisymmetric with respect to the central wavelength of the line. Such profiles are never observed. Sigwarth et al. (1999) and Sánchez Almeida & Lites (2000) found asymmetries in observations with $1''$ angular resolution. Rather than disappearing when improving the angular resolution, they become more common and pronounced at the $0''.32$ angular of Hinode (Viticchié et al. 2010; Viticchié & Sánchez Almeida 2010). Figure 1 illustrates the type of observed asymmetries. It belongs to the work by Viticchié & Sánchez Almeida (2010), and shows all the classes of Stokes V profiles of Fe I $\lambda 6301$ & 6302 observed in the quiet Sun with Hinode/SP. The presence of net circular polarization² in these profiles indicates that (part of) the unresolved structures producing the asymmetries overlap along the line-of-sight (LOS; see Sánchez Almeida 1998) and, therefore, they have to be smaller than the thickness of the photospheric layers where the lines are formed ($\lesssim 100$ km). Consequently, resolving these structures by brute force (i.e., increasing the angular resolution of the observation) is hopeless since the gradients producing the asymmetries occur along the LOS. Some of the observed Stokes V profiles present three lobes revealing that these unresolved structures often have opposite polarities (Sánchez Almeida & Lites 2000; Viticchié et al. 2010).

²The net circular polarization is the wavelength integral of the Stokes V profile, and it is observed to differ from zero.

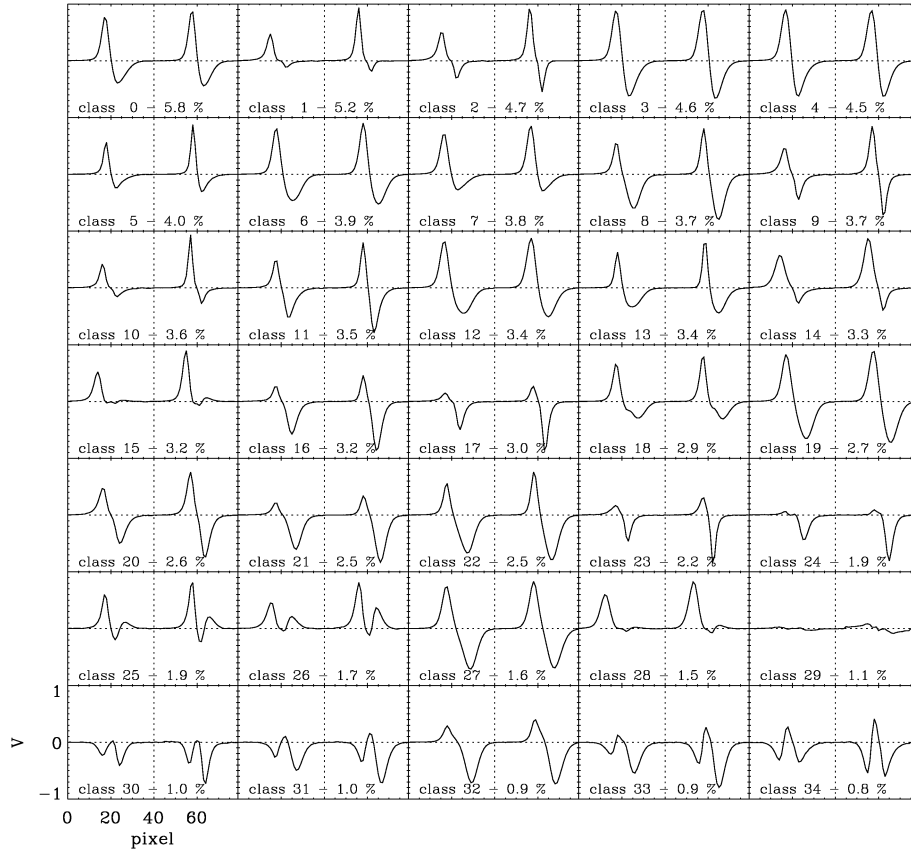


Figure 1. Classes of Stokes V profiles of Fe I $\lambda 6301$ & 6302 observed in the quiet Sun with Hinode/SP (Viticchié & Sánchez Almeida 2010). None of the profiles is antisymmetric, revealing that spatially unresolved magnetic structures are present throughout. Asymmetries go from mild to extreme. The solid lines correspond to the average profiles in the class, whereas the percentages indicate the fraction of observed profiles belonging to the class. Wavelengths increase to the right and are given in pixels (of $21.5 \text{ m}\text{\AA}$).

In short, the complications of the magnetic field in the quiet Sun make all measurements prone to large bias. A proper interpretation requires acknowledging the presence of plasmas with different magnetic properties overlapping along the LOS.

4. Distribution of Magnetic Field Strengths and Unsigned Flux

Both theory and observations suggest a quiet Sun plasma with a wide range of physical properties, therefore, it can be best characterized using probability density functions (PDFs). We will define the magnetic field strength PDF, $P(B)$, as the probability that a point of the photosphere chosen at random has a magnetic field strength B . (For alternative ways of defining quiet Sun PDFs, see, e.g., Steiner 2003, Bommier et al. 2009.) The function $P(B)$ cannot be measured directly – the *points* in the photosphere cannot

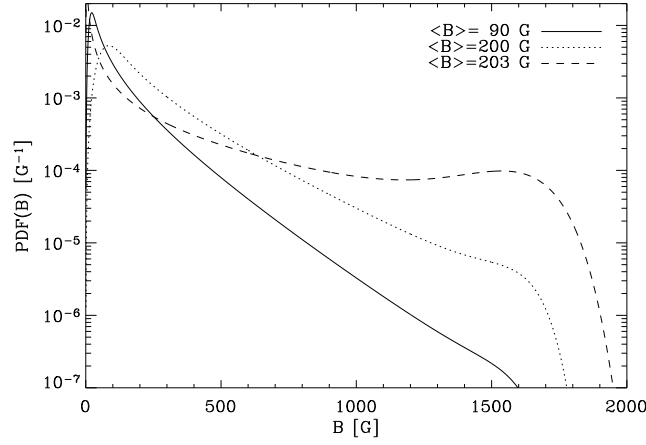


Figure 2. Three magnetic field strength PDFs with the expected shapes. They differ in the mean field (see the inset), and on whether this mean field is mostly provided by the weak fields (the dotted lines) or has a strong contribution of the kG fields (the dashed line).

be spatially resolved, therefore, in order to infer $P(B)$ from histograms of observed B , one must account for the spatial smearing and the biases discussed in § 3. In spite of this disadvantage, the definition is convenient since $P(B)$ is directly predicted by the numerical simulations of magneto-convection (e.g., Cattaneo 1999a; Vögler et al. 2005). In addition, the two first moments of a PDF thus defined have a direct and important physical interpretation: the first moment $\langle B \rangle$ is connected with the unsigned magnetic flux density in the quiet Sun, whereas the second moment provides the magnetic energy density of the quiet Sun $\langle B^2 \rangle / (8\pi)$,

$$\langle B \rangle = \int_0^\infty B P(B) dB, \quad \langle B^2 \rangle = \int_0^\infty B^2 P(B) dB. \quad (2)$$

From an observational viewpoint, the function $P(B)$ is still fairly uncertain. The many different estimates of magnetic field strength existing in the literature seem to be inconsistent, which can be probably pinned down to the biases introduced in the measurements by the complications of the quiet Sun magnetic fields (see § 3). However, despite the discrepancies, there is a general consensus on a few general properties of $P(B)$. All the quiet Sun is magnetic but with a weak field strength – inferior to, say, 1 hG, but differing from zero since $P(B) \rightarrow 0$ when $B \rightarrow 0$ (Domínguez Cerdeña et al. 2006a). In addition, the distribution $P(B)$ should present an extended tail that goes all the way to the maximum possible value at some 2 kG. The three PDFs in Fig. 2 illustrate the overall expected shape, as well as the differences under discussion. (They have been derived following the approximation by Sánchez Almeida 2007, but this fact is unimportant for the sake of our argumentation.) The disagreement is in the (important) details, namely, on the value of $\langle B \rangle$ and on whether this $\langle B \rangle$ is mostly produced by dG, hG or kG magnetic fields. The value of $\langle B \rangle$ determines the importance of the quiet Sun magnetic fields as compared with the classical manifestations of the solar activity (active regions), whereas the relative contribution of the various field strengths

decides the connectivity of the photospheric quiet Sun fields with the rest of the solar atmosphere (see § 7).

We address the issue of the mean field first. Figure 3 shows measurements of the mean unsigned vertical magnetic field, $|\overline{B_z}|$, obtained by many different groups with different instrumentation and different spatial resolution. One can think of $|\overline{B_z}|$ as the average signals in a calibrated magnetogram (even though in some cases the actual measurements involve sophisticated method of diagnostics). All these measurements are based on Zeeman induced polarization signals. The mean vertical field $|\overline{B_z}|$ is a *biased* estimate of $\langle B \rangle$ since

$$|\overline{B_z}| \longrightarrow \beta \langle B \rangle, \quad (3)$$

in noiseless observations with ∞ spatial resolution, i.e., in observations free from the biases described in § 3. The factor β depends on the distribution of magnetic field inclinations but it is of order one in the extreme cases of vertical fields ($\beta = 1$) and isotropic distribution ($\beta = 0.5$). Note the clear trend for $|\overline{B_z}|$ to increase with increasing angular resolution (i.e., with decreasing size of the resolution element L). The solid line in Fig. 3 corresponds to a fit $|\overline{B_z}| \propto L^{-1}$, which is the behavior expected in the case of polarization signals produced by the random association of equal independent structures with size l smaller than L (Sánchez Almeida 2009). In this oversimplified model $|\overline{B_z}| \simeq \langle B \rangle$ when the structures are resolved (i.e., when $L \simeq l$), so the linear extrapolation predicts a flux of 36 G or 181 G depending on whether the intrinsic size l is 100 km or 20 km, respectively. This extrapolation is not free from ambiguity, though. In addition to the validity of the extrapolation, the main problem has to do with the large scatter of among the $|\overline{B_z}|$ obtained with the best present observations (they are labeled as Hinode in Fig. 3, plus the point by Martínez González 2010 corresponding to the magnetograph IMAx on-board the balloon SUNRISE; see Martínez Pillet et al. 2010). They span the range between 10 G and 35 G. Moreover, the measurements of lowest unsigned flux density hint at a saturation at some 10 G which, if real, would make the above extrapolation meaningless. Our guess is that the apparent inconsistencies are mostly set by the unaccounted biases of the different diagnostic techniques (as discussed in § 3), therefore, they will be eventually cured once those biases become properly understood. However, this remains to be demonstrated, and fixing out such inconsistencies is one of the major goals of the quiet Sun physics today. All these uncertainties notwithstanding, we think that the present observations favor a quiet Sun mean field $\langle B \rangle$ between 1 and 2 hG. As explained above, this high unsigned flux is compatible with the observed Zeeman signals if, as expected, we do not resolve the quiet Sun magnetic structures yet (§ 3). Moreover, Hanle depolarization signals provide an independent estimate of $\langle B \rangle$ (at least of the contribution to the mean magnetic field by B less than a few hundred G; see, § 3). In order to explain the observations of Sr I $\lambda 4607$, a mean magnetic field in excess of 1 hG seems to be required (Sánchez Almeida et al. 2003a; Trujillo Bueno et al. 2004; Bommier et al. 2005). Again, this estimate is not free from ambiguity since it heavily relies on modeling (c.f., Faurobert-Scholl 1993; Trujillo Bueno et al. 2004), and on the assumption of the shape of $P(B)$ (Trujillo Bueno et al. 2004; Sánchez Almeida 2005). However, both Zeeman and Hanle signals seems to agree in the high $\langle B \rangle$ value. Note that the unsigned flux density we advocate is one order of magnitude larger than the unsigned flux density in the form of active regions, even during the maximum of the solar cycle (Harvey-Angle 1993; Sánchez Almeida 2003; Sánchez Almeida 2009).

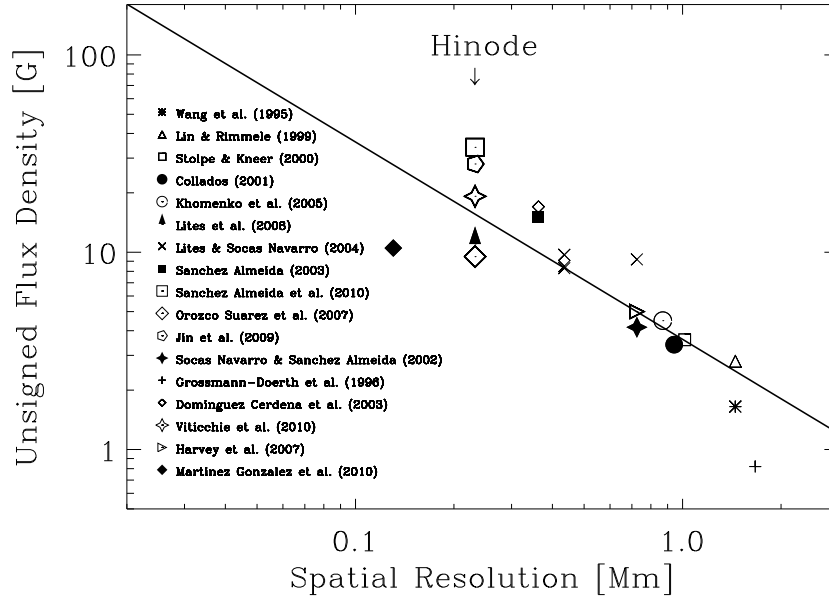


Figure 3. Mean magnetograph signal (unsigned flux density) observed in quiet Sun regions as function of the spatial resolution of the observation. Each symbol corresponds to a different measurement identified with the appropriate reference in the inset. The solid line represents a straight line of slope minus one fitted to the data. It predicts a flux of 36 G and 181 G for resolutions of 100 km and 20 km, respectively. Note the large scatter at the highest spatial resolutions. This plot is an undated version of Fig. 1 in Sánchez Almeida (2009).

Another aspect of considerable importance, and bitter debate in the literature, is the distribution of magnetic field strengths, i.e., the shape of $P(B)$. Assume the mean field to be known. Is it representative of the most probable field in the quiet Sun (the peak of the PDF) or, rather, is it much larger and provided by the tail of kG fields? Even though most of the quiet Sun has $B < 1$ hG (see Fig. 2), the kG fields may supersede the contribution of the dG since their relative importance scale as $\sim 10^4 \cdot P(1 \text{ kG})/P(1 \text{ dG})$ (see Eq. [2] with $dB \sim B$). Whether or not the kG significantly contribute to the quiet Sun magnetic flux budget depends on the unknown details of $P(B)$. The debate is illustrated by two of the PDFs shown in Fig. 2. The mean field of the dotted and the dashed lines is the same (≈ 2 hG), but in one case half of it is provided by the kGs (the dashed line) whereas kGs contribute with only 0.5% in the second case (the dotted line). As discussed in § 3, all the individual measurements of the field strength are strongly biased, therefore, one would need to piece together several Hanle and Zeeman measurements with complementary biases to infer the full PDF shape. However, this exercise has not been properly done yet. (Domínguez Cerdana et al. 2006a indicate the pathway.) The discussions and conclusions found in the literature rely on single measurements. Most of these measurements favor little contribution of the kG fields with respect to the hG fields (Keller et al. 1994; Lin 1995; Khomenko et al. 2003; López Ariste et al. 2006, 2007; Orozco Suárez et al. 2007; Asensio Ramos et al. 2007; Martínez González et al.

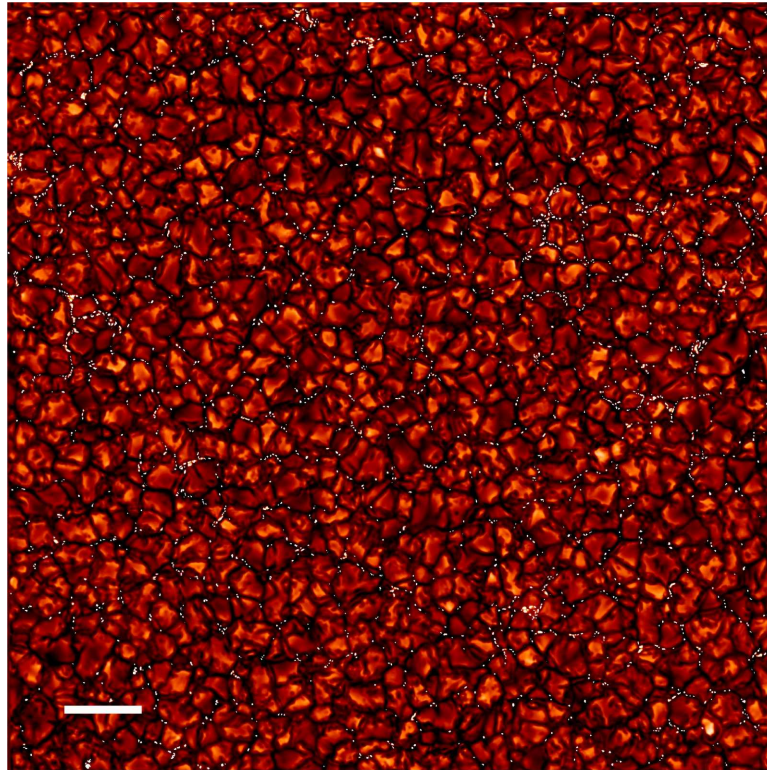


Figure 4. G-band image of the quiet Sun at the disk center with the observed Bright Points (BPs) enhanced. BPs are thought to trace kG magnetic concentrations, and they are found throughout, with a number density equivalent to 1.2 BPs per granule. The scale at the bottom left corner corresponds to 5 Mm. Adapted from Sánchez Almeida et al. (2010, Fig. 1).

2008b; Asensio Ramos 2009; Ishikawa & Tsuneta 2009; Beck & Rezaei 2009). However, there is a minority of works where the presence of kG fields in the quiet Sun stands out (Sánchez Almeida & Lites 2000; Socas-Navarro & Sánchez Almeida 2002; Sánchez Almeida et al. 2003; Domínguez Cerdeña et al. 2006b; Viticchié et al. 2010). One may say that the observations disfavor the relevance of kG fields. However, from our point of view, the debate has not been settled yet. First, the information on the magnetic field strength is coded in the shape of the line polarization and, thus, it is extracted by carefully reproducing those shapes by inversion (e.g., Skumanich & Lites 1987; Ruiz Cobo & del Toro Iniesta 1992; Sánchez Almeida 1997). It turns out that, so far, the only works reproducing the observed strongly asymmetric line shapes reveal kG fields. Second, the high angular resolution images of the quiet Sun show the ubiquitous presence of bright points (BPs) in the intergranular lanes (Sánchez Almeida et al. 2004; de Wijn et al. 2005, 2008; Bovelet & Wiehr 2008; Sánchez Almeida et al. 2007; Sánchez Almeida et al. 2010, see Fig. 4), which are thought to trace kG magnetic concentrations (Spruit 1976; Carlsson et al. 2004; Keller et al. 2004). The most recent counting indicates that at least 1% of the quiet Sun solar surface is covered by these BPs (i.e., by kG fields). Such large fraction of kG is consistent with the filling factors

of the kG-heavy PDFs (Viticchié et al. 2010), but it is far in excess of the most common works. In any case, much work on the shape of $P(B)$ remains to be done.

5. Distribution of Magnetic Field Inclinations

The numerical models predict a magnetic field with all inclinations from 0° to 180° (§ 2). The presence of a wide range of inclinations is also clear from an observational point of view. Martin (1988) finds the longitudinal component of internetwork (IN) magnetic fields to be present everywhere in the solar disk, arguing the need for all inclinations to be present. Similar arguments have been put forward more recently by others (e.g., Meunier et al. 1998; Lites 2002; Harvey et al. 2007). In particular, the work of Martínez González et al. (2008a) presents observations of the $1.56 \mu\text{m}$ spectral lines at different positions on the disk, from the center to an heliocentric angle of 63° . At their spatial resolution ($0''.8$), both circular and linear polarization are present in at least 95% of the field of view in all maps. There is no trend in the observed ratio circular-to-linear polarization signals from the disk center to the limb. This means that the magnetic field at the quietest areas of the Sun must not have a preferred direction or, in other words, the distribution of magnetic fields should be quasi-isotropic. After these results, many recent works based on the spectro-polarimetric data from Hinode have given a different view of the quiet Sun magnetic fields. Lites et al. (2008) and Jin et al. (2009) have shown that the transverse component of the magnetic field is some five times more important than the vertical one. This is an observational fact that, to our opinion, has been misunderstood, leading people to affirm that magnetic fields in the quiet Sun are mostly horizontal (e.g., Orozco Suárez et al. 2007; Ishikawa & Tsuneta 2009). The excitement produced by these often-called *transient horizontal fields* has led to many papers only dedicated to the detailed analysis of the magnetic fields inclined around 90° , forgetting that the whole picture of the quiet Sun magnetism must come with the entire vector magnetic field distribution. We think that these new results can be reconciled with the quiet Sun magnetic fields to be (quasi-)isotropically distributed. An isotropic magnetic field has a PDF of inclinations given by

$$P(\theta) = \frac{\sin \theta}{2}, \quad (4)$$

being $0 \leq \theta \leq 180^\circ$ the inclination with respect to any reference direction. From this equation we see that the probability is maximum at $\theta = 90^\circ$, hence for transverse fields choosing as reference the LOS direction. At first, the fact that most magnetic fields are transverse to the LOS in an isotropic distribution is counterintuitive. However, it arises from the fact that for the magnetic field to be LOS aligned it has to point in a specific direction, however, for the field to be transverse many different directions are possible. Figure 5 shows the histograms of magnetic field inclinations derived by Orozco Suárez et al. (2007); Ishikawa & Tsuneta (2009) and Bommier et al. (2009). Except for the dip at 90° and the peaks at 0 and 180° , the distribution is consistent with an isotropic distribution with some scatter (shown as the solid line in Fig. 5). The deviation at 0 and 180° can be easily explained as a real effect associated with the kG fields, that tend to be vertical (e.g. Schüssler 1986; Martínez González et al. 2008a), whereas the dip at 90° may be an observational bias due to the presence of unresolved structure. Recently, the Bayesian approach of Asensio Ramos (2009) has shown that, using the

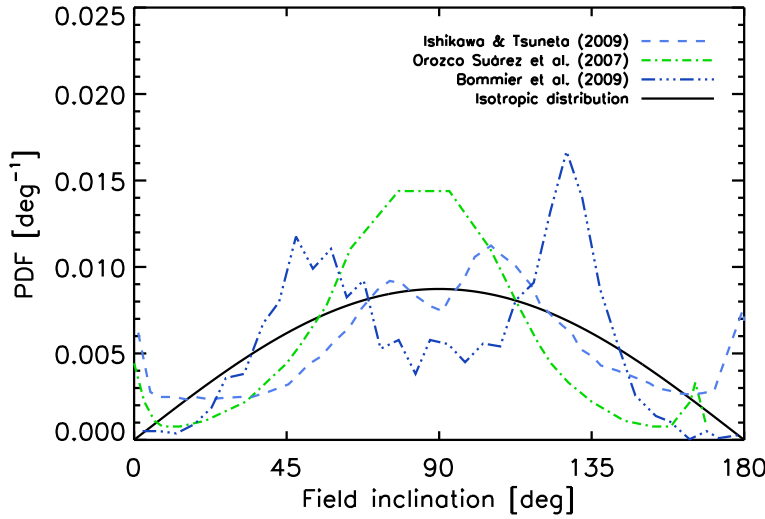


Figure 5. Distributions of quiet Sun magnetic field inclinations as derived by various groups (see the inset). They are roughly consistent with an isotropic distribution (the solid line). The deviations at 0° , 90° , and 180° are discussed in the main text.

same data and modeling as Orozco Suárez et al. (2007), the observations obtained with Hinode are compatible with a quasi-isotropic distribution of magnetic fields.

As we mentioned above, the measurements by Lites et al. (2008) and Jin et al. (2009) lead to an apparent transverse field five times larger than the longitudinal magnetic field. Is this observational result also consistent with an isotropic distribution of magnetic fields? The answer is yes. The inference of these large mean transverse magnetic fields is based on assuming the magnetic field structure to be spatially resolved at Hinode spatial resolution ($0''.32$). However, there is no clear reason why this should be a good assumption (see § 3). If it is relaxed then the apparent transverse magnetic field B_{app}^T and the apparent longitudinal magnetic field B_{app}^L scale differently with the fraction of resolution element filled by magnetic structures α , i.e.,

$$\begin{aligned} B_{\text{app}}^L &= \alpha B \cos \theta, \\ B_{\text{app}}^T &= \sqrt{\alpha} B \sin \theta. \end{aligned} \quad (5)$$

(See, e.g., Landi Degl'Innocenti & Landolfi 2004.) Therefore, if $\alpha \neq 1$, then the apparent transverse magnetic field is artificially inflated with respect to the longitudinal component by a factor $1/\sqrt{\alpha}$, which can be very large for small values of the filling factor. For example, an isotropic distribution has $\langle |\cos \theta| \rangle = 1/2$ and $\langle |\sin \theta| \rangle = \pi/4$, therefore, if $\alpha \simeq 0.1$, then

$$\frac{\langle |B_{\text{app}}^T| \rangle}{\langle |B_{\text{app}}^L| \rangle} = \frac{\pi}{2\sqrt{\alpha}} \simeq 5, \quad (6)$$

in agreement with the observed ratio.

The complex quiet Sun magnetic fields may be viewed as a collection of loops connecting the solar interior and the outer atmosphere (see § 6.1). The observed PDF

of inclination sets constraints on the properties of those loops as illustrated by the following naive example. Assume the quiet Sun to be made out of semi-circular loops fully contained in the photosphere. The distribution of inclinations along each loop is uniform (i.e., all inclinations are equally probable), therefore, a collection of such loops would also have a uniform distribution. A uniform distribution is inconsistent with the observed quasi-isotropic distribution and, therefore, the quiet Sun is not a collection of semi-circular loops. Obviously this is just an academic example, but it illustrates the prospects for the magnetic field inclination PDF to constrain the loop properties, a diagnostic potential that will have to be developed and eventually exploited.

6. Time Evolution on Short and Long Time-Scales

6.1. Variations on Short Time-Scales: Loop Emergence

The quiet Sun magnetograms evolve on a time-scale as short as that of the granulation (say, 10 min and shorter; see, e.g., Lin & Rimmele 1999; Harvey et al. 2007; Centeno et al. 2007; Ishikawa & Tsuneta 2009). The quiet Sun fields are dragged along by horizontal plasma motions (e.g., Zhang et al. 1998; Domínguez Cerdeña et al. 2003b) and, therefore, they tend to accumulate where these motions are smallest. As a result of this transport, all spatial scales of organized photospheric motions appear in the quiet Sun magnetograms including granulation and mesogranulation (Domínguez Cerdeña et al. 2003b; Domínguez Cerdeña 2003). The corresponding time-scales are also observed: the mesogranular pattern lasts at least half an hour (Domínguez Cerdeña et al. 2003b), whereas the lifetimes of the large IN patches is of the order of a few hours (Zhang et al. 1998). It is evident that the time-scales for the variation of the quiet Sun fields are much shorter than those characterizing the evolution of active regions (several days; see, e.g., Harvey-Angle 1993).

At the shortest time-scales, the magnetic fields emerge as small looplike structures preferentially in the center of the granules (Martínez González et al. 2007; Centeno et al. 2007; Martínez González & Bellot Rubio 2009). Loops are to be expected as the result of the uplift of subsurface magnetic structures transported by convective motions (e.g., Cattaneo 1999a; Yelles Chaouche et al. 2009). The emergence rate of such small-scale loops is 0.2 loops per hour and arcsec^2 , which brings $1.1 \times 10^{11} \text{ Mx s}^{-1} \text{ arcsec}^{-2}$ of new flux to the solar surface. Initially, the loops are observed as small patches of linear polarization above a granular cell. Shortly afterward, two footpoints of opposite polarity become visible in circular polarization within or at the edges of the granule and start moving toward the adjacent intergranular space. Interestingly, 23% of the loops that emerge in the photosphere reach the chromosphere (Martínez González & Bellot Rubio 2009). The reconstructed time evolution of such an emergent loop event is plotted in Fig. 6. When the magnetic field emerges into the quiet surface the loop presents a flattened, staple-like geometry and it maintains this geometry across the photosphere. The loop in Fig. 6 has a mean magnetic field strength of $B \sim 200 \text{ G}$ occupying 30% of the resolution element. Beyond the photosphere the loop develops an arch-like geometry and its top rises at $\sim 12 \text{ km s}^{-1}$, close to the sound speed in the chromosphere. The dynamics of the emergence process can more complicated. Figure 7 shows the 3D topology of the magnetic field associated with one of these events, where the flux emerges in a preexisting granule as a structure showing a simple bipolar loop with a clear preferred azimuth before developing a full three-dimensional structure and dynamics. A conservative estimate of the magnetic energy injection is $2.2 \times 10^7 \text{ erg cm}^{-2} \text{ s}^{-1}$, which is of the same

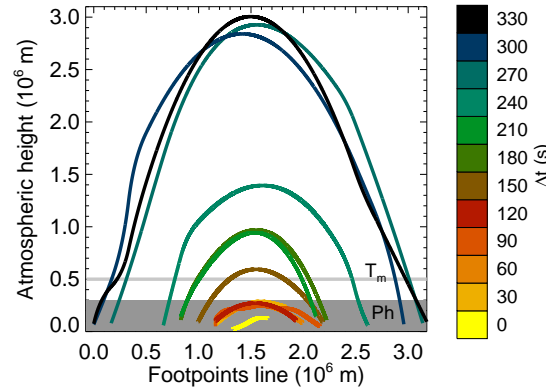


Figure 6. Ascent of a small magnetic loop through the quiet solar atmosphere. Since the azimuth always lies along the line connecting the footpoints of the loop, the structure is collapsed to a plane. For each time the reconstructed loop is represented with different colors, from blue to orange as time increases. The gray area labeled *Ph* represents the photosphere. The gray line labeled T_m represents the mean height for the temperature minimum region. The apex of the loop rises with a velocity of $\sim 3 \text{ km s}^{-1}$ in the photosphere. Beyond the temperature minimum, the apex of the loop ascends at $\sim 12 \text{ km s}^{-1}$, close to the sound speed in the chromosphere.

order of the estimated radiative losses for the chromosphere. (Martínez González et al. 2010)

6.2. Variations With the 11-year Cycle

Little is known about this central issue. If, as discussed in § 2, the quiet Sun magnetic fields are not generated by the global solar dynamo, then one expects no variation of the quiet Sun magnetic fields with the solar cycle. On the contrary, if they were observed to vary, it would show the existence of a physical connection between quiet Sun and active regions. Faurobert et al. (2001) find a factor 2 variation of the mean field derived from Hanle signals. Sánchez Almeida (2003) claims no variation within a 40 % error bar. Shchukina & Trujillo Bueno (2003) also find no variation. The data of the first four years of operation of the SOLIS magnetogram (Keller et al. 2003) show no obvious sign of variation (Harvey 2010). The Hanle scattering polarization signals of C_2 do not vary with the cycle (Stenflo et al. 2010, these proceedings). Based on this limited information, we can conjecture that the quiet Sun magnetic flux does not seem to suffer large variations along the cycle. If it does, the variations are far smaller than those observed in active regions, whose total flux varies by more than one order of magnitude (e.g., Harvey-Angle 1993, Chapter 12, Fig. 4)

7. Why is the Quiet Sun Magnetism Important?

The quiet Sun is the component of the solar surface magnetism that seems to carry most of the magnetic flux and magnetic energy (§ 4). This fact makes it potentially important to understand the global magnetic properties of the Sun (solar dynamo, coronal heating, origin of the solar wind, and so on). The potentials are starting to be acknowledged but

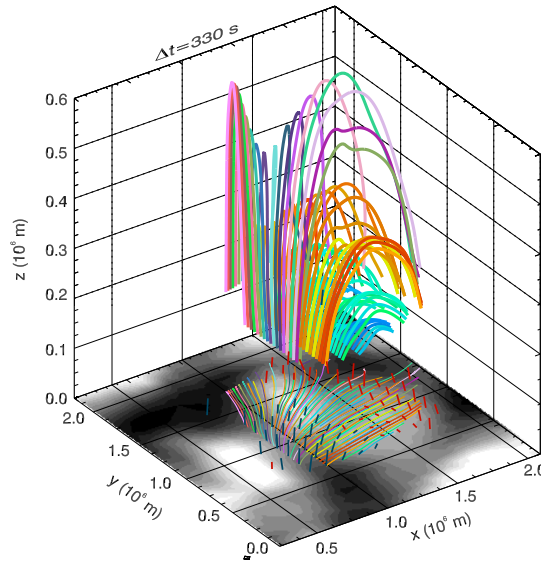


Figure 7. Three-dimensional topology of the magnetic field over a granule. The continuum image at the bottom shows granular (bright) and intergranular (dark) regions. Short lines indicate magnetic field orientation (blue for the footpoint with positive, emergent polarity; red for the negative footpoint), derived from inversion of the lines Fe I $\lambda 6301$ & $\lambda 6302$ at the points with high enough polarization. Representative field lines (tangent to these director vectors) are calculated starting at the height of formation of the Fe I lines at one footpoint and followed until they reach the same height at the other end. Both footpoints happen to be connected. The projection of field lines on the solar surface appear as colored lines on the bottom plane, showing azimuth spreading over nearly 90° . From low-lying bluish lines to high-lying ones the magnetic field fills most of the volume from the photosphere to the low-chromosphere. The colors of field lines have been used for the ease of eye. Adapted from Martínez González et al. (2010)

the true relevance is hard to foresee. The section mentions some of the exploratory works analyzing the impact of the traditionally neglected quiet Sun magnetic fields.

Schrijver & Title (2003) study the influence of the quiet Sun magnetic fields on the extrapolation of the photospheric field to the corona. They conclude that an important modification of the network field lines is induced by the presence of the quiet Sun fields, implying that a significant part of these disorganized photospheric fields do indeed reach the quiet corona. Similar conclusions have been independently inferred by others (e.g., Goodman 2004; Jendersie & Peter 2006). Inspired by these works, there has been inconclusive attempts to find footpoints of transition region loops in the interior of supergranulation cells (Sánchez Almeida 2007; Judge & Centeno 2008). However, the connection between the photosphere and the outer atmosphere has been clearly established by the newly discovered granule-size loops that are continuously popping from the solar interior (see § 6.1). Their signatures are clearly seeing in chromospheric lines after abandoning the photosphere, and there is no reason to believe that the ascension will stop there (Martínez González & Bellot Rubio 2009). Moreover, the amount of magnetic energy transported by these rising loops is enough to balance the radiative losses of the chromosphere (§ 6.1). The problem arises as to how this

energy is transformed into heat. Recent magneto-hydrodynamic (MHD) simulations suggest that the small loops reach chromospheric heights and get reconnected with the local magnetic fields, heating the plasma and generating MHD waves that propagate into the corona (Isobe et al. 2008). Another source of heating could be the Joule dissipation of magnetic energy involved in the reconnection, in the spirit of the classical Parker's microflaring activity (Parker 1994). As we mention in § 4, a part of the quiet Sun fields are in the form of vertical kG magnetic concentrations. Those fields can provide a mechanical connection between the photosphere and the upper atmosphere, e.g., as waveguides for the propagation of MHD waves excited by photospheric motions (e.g., van Ballegoijen et al. 1998; Nisenson et al. 2003; Viticchié et al. 2006; Bonet et al. 2008). Actually, magneto-acoustic oscillations that can propagate upward have been recently detected (Martínez Gonzalez et al. 2010). They do not seem to be a characteristic mode of oscillations of the magnetic structures but due to the forcing by granular motions. Interestingly, the same magneto-acoustic oscillations have been found upper in the photosphere, suggesting that there is indeed propagation of some power to higher layers.

The physical processes that accelerate the solar wind remain unknown. The wind is present on the Sun at all times, even during solar minimum, therefore, the role of quiet Sun fields on its production cannot be discarded. This problem has been recently addressed by Cranmer & van Ballegoijen (2010). They study the impact of the reconnection of closed loops driven by photospheric motions that try to be realistic. It was found unlikely that either the slow or fast solar wind are driven by such reconnection, but further work is required.

The solar metallicity is used as reference in astrophysics so, if it is revised, then the metal content of the universe is automatically revised, with the subsequent implications on diverse areas spanning from stellar evolution to cosmology. It turns out that the solar metallicity has been modified by a factor 1/2 two during the last decade (Asplund 2005; Asplund et al. 2009, and references therein). This major change has been mostly driven by the use of realistic 3D numerical models of the solar photosphere to synthesize spectral lines (Stein & Nordlund 1998). These numerical models do not include the quiet Sun magnetic fields, which is a good approximation from the traditional standpoint where the quiet Sun was non-magnetic. However, if a mean field of 1-2 hG pervades the quiet Sun (§ 4), it should modify the convective transport in the photospheric layers, and so the temperature stratification that determines the line formation and the abundance. In exploratory works, Borrero (2008) and Fabbian et al. (2010) have considered the influence of the quiet Sun fields on the solar metallicity estimates, founding it to be important. The presence of quiet Sun magnetic fields forces us to reduce the inferred metallicity by an additional 10% (Fabbian et al. 2010).

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